Nature's Monte Carlo Experiments in Sustainability

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Abstract.- It has been made clear in the literature that management must simultaneously 1) apply consistently to individual species, ecosystems, and the biosphere; 2) account for complexity, stochasticity, processes, mechanics, dynamics, uncertainty, unknowns, and all scales of time and space; 3) maintain components of each level of biological organization within their normal ranges of natural variation; 4) exercise precaution by considering risk in achieving sustainability; 5) be information-based and interdisciplinary in approach; 6) include monitoring, assessment, and objectives; 7) recognize that control is limited primarily to human action; and 8) include humans as components of inclusive living systems.

These requirements for management may seem impossible, especially when combined. But there is a way to proceed. Management action could be guided by frequency distributions of empirical examples of sustainability, to ensure that human presence and influence in living systems fall within the normal ranges of natural variation. In regard to fisheries management, this applies to such things as resource utilization rates. For example, frequency distributions among species according to the rates that they consume a particular prey species demonstrate both variation and limits. Similar distributions occur for other ways of measuring a species. These include biomass consumption within particular ecosystems and numbers of resource species consumed. The central tendencies of such distributions for consumption rates serve as estimates of ecologically sustainable yields (ESY) or rates (ESYR), that can be used in place of methodologies currently in place (e.g., the "Fs" of conventional approaches in fisheries management).

Species frequency distributions reflect the results of the trial-and-error processes of natural selection, including selective extinction and speciation. They emerge from the complexity of reality and exposure to it. This reality includes all processes, mechanics, and materials. Species, and the individuals that comprise them, may be seen as physical Monte Carlo models in a kind of natural Bayesian integration process. These models are tested empirically against the risks and limitations of the realities of their environment. Extinction and associated risks are accounted for because existing species, as represented in frequency distributions, have not succumbed to risks leading to extinction that has removed billions of species as failures in the grand natural experiment. Collective risks prevent the accumulation of species in the tails of species frequency distributions and especially beyond the normal ranges of natural variation.

Sample applications of this approach at ecosystem and single-species levels use marine mammals as empirical examples of sustainable resource consumption rates. These same species may also serve as resource species for human consumption exemplified by the subsistance taking of northern fur seals. In this approach, science, monitoring and assessment are involved in 1) documenting the normal ranges of natural variation among species and ecosystems, 2) monitoring human progress in finding a position within the normal range of natural variation, and 3) observing other species and ecosystems as they respond, presumably to regain positions within normal ranges of natural variation in reaction to human change, the change over which we have some control.

Introduction

There is a voluminous accumulation of literature on management and the ways it would apply in consideration of, or application to, ecosystems (e.g., Grumbine 1994, Christensen et al. 1996, Mangel et al. 1996, Czech and Krausman 1997, Grumbine 1997, Fowler in prep.). It is clear that management must meet a number of criteria to be acceptable. In particular, any form of management adopted must successfully apply in the realm of natural resources such as management of commercial fisheries, the primary focus of this paper. The criteria which must be met by management are numerous but can be distilled into 8 essential elements, all of which must apply simultaneously (Table 1).

On the surface, it would seem impossible to find a form of management that meets the combination of these requirements by adhering to all of the underlying principles. Nevertheless, it can be done. At least one way of accomplishing this task is by using other species as empirical examples of sustainability. Consider, for example, the take ("harvest" or consumption) of biomass from either an ecosystem or a resource species. Rates of consumption by heterotrophic consumers can be used to form distributions that provide information regarding empirically observed sustainability. Action is then guided by the information (Criterion 5, Table 1) found in such frequency distributions each of which exhibits natural variation and limits.

Table 1. A list of criteria that must be met by any form of management that applies to the management of human use of natural resources (see, e.g., Grumbine 1994, Christensen et al. 1996, Mangel et al. 1996, Czech and Krausman 1997, Grumbine 1997, Fowler in prep.).

1) Any form of management must apply simultaneously at the various levels of biological organization, and it must do so consistently, without conflict. In other words, management applied in the management of the harvest of biomass from individual resource species must be compatible with the harvest of biomass from the ecosystems in which the harvested species occur. Similarly, biomass consumption by humans from the biosphere must be guided by principles that are not in conflict with those guiding the harvest of biomass from either an individual resource species or any particular ecosystem.

2) Management action must be based on a process that accounts for reality in its complexity over the various scales of time, space, and biological organization. The context of environmental factors must be accounted for along with the elements of stochasticity and the diversity of processes, mechanics, and dynamics. It must be possible to consider the complexity of organizational structure, elements, compounds, organs, chemicals, and physical and chemical processes. Furthermore, we must be able to consider uncertainty and the unknowns within the complexity of things. Some of these are truly unknowable, but there must be a way for them to be taken into account.

3) A core principle of management is that of maintaining individuals, species, and ecosystems within their respective normal ranges of natural variation as components of the more aggregated levels of biological organization (Rapport et al. 1981, Rapport, Regier, and Hutchinson 1985, Christensen et al. 1996, Holling and Meffe 1996, Mangel et al. 1996). Any form of management must apply this principle.

4) Management must be risk-averse in exercising precaution to achieve sustainability. Sustainability is, by definition, not achieved by any form of management that generates risk rather than minimizing it.

5) Guidance must be available to management in the form of information that provides goals and objectives. This information must be based on interdisciplinary approaches in the sense of meeting Criterion 2 above.

6) Management must include monitoring, assessment, and objectives, not only to produce the information that is used for guidance (Criterion 5), but also for evaluation of progress in achieving established goals and objectives.

7) It must be recognized that control over other species and ecosystems is impossible (Christensen et al. 1996, Holling and Meffe 1996, Mangel et al. 1996). The only option for control is the control of human action. We can control fishing effort but not the resource population. We can influence the resource population, but not control it or the indirect changes brought about by our influence. The guidance that we need for management is guidance regarding the level of influence (e.g., harvest rate) that meets the other criteria of this list.

8) Humans must be allowed to be components of at least some ecosystems to avoid unrealistically precluding human existence.

All heterotrophic species, including humans, consume biomass. This consumption influences other species and ecosystems. Management actions, in the approach described here, would ensure that human presence (Criterion 8, Table 1) and influence in living systems would fall within the normal ranges of natural variation (Criterion 3). More specifically, the goals and objectives (Criteria 5 and 6) would be provided by the central tendencies of frequency distributions of consumption rates among other species. This is management guided by using other species as empirical examples of sustainability and is concerned with controlling human influence (Criterion 7) rather than controlling population levels of resource species or the composition of the ecosystems.

Examples of the ways this approach works are presented below in more detail. Preliminary elements of the application of this process are presented for application at two levels of biological organization: the ecosystem and single species.

Ecosystem Application

This section treats one part of the first criterion of Table 1: application of management at the level of the ecosystem. Management at any level must be able to address a number of important questions. With an ecosystem in mind, one important question is: "What is the most sustainable level of biomass consumption from this ecosystem?" Figure 1 shows the frequency distribution for one set of estimated rates of consumption for a set of individual species from a single ecosystem. This distribution is for 24 species of marine mammals and birds that consume from the Georges Bank ecosystem according to their rates of consumption (measured as the $\log_{10}$ of biomass consumed in thousands of metric tons annually). These species thus serve as examples of sustainability, only a small part of which is their role as competitors with humans and other species.

In concept, the application of information such as shown in Figure 1 is simple. Using non-human species as examples of sustainability becomes a matter of confining human consumption (commercial harvest) of biomass to catch rates within the bounds of the range shown in Figure 1 (Criteria 3 and 7, Table 1). To be risk-aversive and precautionary (Criterion 4, Table 1), commercial harvests would be conducted at levels near the central tendencies of such distributions. This would avoid the risks and constraints posed by the overall system (including ecosystem) to prevent the accumulation of species in the tails of such distributions.

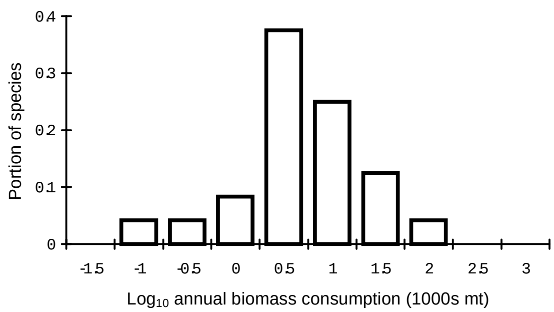

Figure 1. A species frequency distribution representing the Georges Bank ecosystem, showing variability among 24 species of marine mammals and birds as distributed according to estimated annual biomass consumption (log thousands of metric tons) within this region (from Backus and Bourne 1986). Each bar represents the fraction of the 24 species found in the category corresponding to the labeled rate of resource consumption.

Maximizing sustainability is largely a matter of minimizing risk. The "harvest rates" near the central tendencies (such as the mode of distributions like those shown in Fig. 1) are given greater emphasis in being represented by more numerous examples of sustainability (a kind of statistical weighting) than are the examples in the tails of the distributions. These central tendencies provide specific measures that define goals or objectives for management (Criteria 5 and 6, Table 1). Long time scales are accounted for (Criterion 2, Table 1) by virtue of the evolutionary dynamics behind the development of characteristics that contribute to the occurrence of such rates. Thus, frequency distributions among species account for the collective risks on various temporal and spatial scales (Criterion 2, Table 1). These risks include the dynamics of selective extinction and speciation (Lewontin 1970, Slatkin 1981, Arnold and Fristrup 1982, Fowler and MacMahon 1982, Levinton 1988, Eldredge 1989, Williams 1992, Fowler in prep), with extinction as one of the risks that prevent the accumulation of species in the tails of such distributions.

In practice, however, there are a number of factors to take into account that complicate application of management based on empirical examples of sustainability. For example, the specific data in Figure 1 may be subject to bias. We would want to account for any recent human influence through the effects of commercial fishing in the Georges Bank ecosystem. This influence may have altered the frequency distribution shown in Figure 1 to result in broader ranges of variation, shifted position of the mean, or an altered shape compared to what would be expected under circumstances wherein human influence would be within the normal ranges of natural variation.

Other factors also come into play. For example, at this point it is not known how stable a distribution like that of Figure 1 is over time. To be better prepared to apply the proposed approach, it is important to have a frequency distribution that provides averages to account for temporal variation. Ideally, we would emphasize mean consumption rates for species that have been part of the ecosystem over evolutionary time scales (e.g., evolved as part of the ecosystem) and place less importance on species that are recent arrivals to the system (e.g., translocated species). Finally, distributions such as that of Figure 1 are subject to variation owing to the procedures used to estimate consumption rates. Other factors will be treated below.

Single-species Application

A second part of the first criterion in Table 1 requires that any form of management adopted must also apply at the single-species level. In an example parallel to that above for ecosystems, it must apply to the harvest of any single species used for human consumption. Here, we must be able to address a different set of important questions. Among them is: "What is the most sustainable level of biomass consumption from the species being considered as a resource?" We must proceed beyond the conventional treatment of this question to find answers that consider more than population dynamics. We must be able to claim to have met Criterion 2 (Table 1), including consideration of evolutionary dynamics and genetic effects of harvesting (see Law et al. 1993, and the references therein plus: Policansky 1993, Rijnsdorp 1993).

Figure 2 depicts frequency distributions showing variability for estimated total annual consumption among consumers from four individual resource species. Each distribution represents a variety of marine mammals, birds, and fishes as consumers of biomass from each one of the resource species. Each consumer species is represented in one of the bars according to its estimated level of consumption. If we knew the total standing stock biomass of each resource species, these consumption rates could be expressed as a portion of the standing stock biomass (or its log conversion). This would be a specific or relative rate compared to the crude rates of both Figs. 1 and 2.

Adhering to the principles of management behind the criteria of Table 1 is the same as it was for ecosystems. The concept is simply a matter of confining human consumption of biomass (i.e., commercial harvest of biomass) to rates within the normal range of variation shown for each species of those shown in Figure 2 that we choose to use as a resource. Risk-aversive and precautionary measures would be accomplished by regulating commercial harvests (biomass consumption) from each resource species so that these harvests would fall near the central tendencies of such distributions. This avoids the risks that prevent species from accumulating in the tails of such distributions. Long-term optimal sustainability, which can be referred to as ecologically sustainable yield (ESY for the yield, ESYR for the rate), would be achieved in takes corresponding to the central tendencies of such distributions. As with ecosystems, temporal scales much longer than currently considered are accounted for through the evolutionary dynamics that influence the development of characteristic rates of consumption especially those represented by the most numerous examples of empirically observed sustainability.

In parallel with the ecosystem example above, there are factors that must be considered in regard to their influence on these sets of data. The potential biases of the data in Figure 2 may again include human influence. These should be accounted for to avoid misleading advice derived from any abnormal variation, modified mean, or other unnatural shape of the probability distributions represented by Figure 2. Changes in such distributions over time, as well as their differences among various types of resource species are factors to take into account. Patterns related to features such as life history strategy, environmental conditions, body size, or metabolic rates would be of importance.

Thus, in both the ecosystem application, and the single-species application, it is important to avoid any of several ways of misinterpreting such data. For example, homeothermic species similar in body size to humans are likely to be better examples of sustainability for our species than heterotherms with a body mass of 1 gram. We must account for any correlation between consumption rates and characteristics such as body size or metabolic rate to best find representative examples of sustainability applicable to humans. Further studies will be necessary to determine if there are subsets of data that better represent the normal ranges of natural

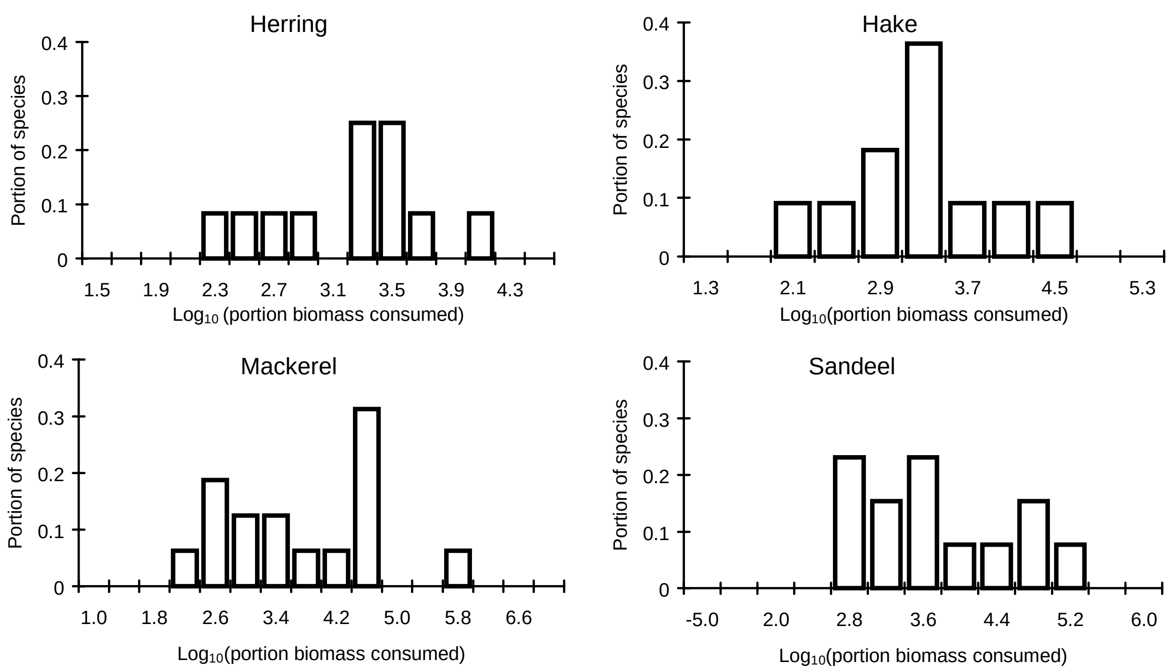

Figure 2. -The frequency distribution of non-human vertebrate species that consume hake (*Merluccius bilinearis*), herring (*Clupea harengus*), mackerel (*Scomber scombrus*), and sandeel (*Ammodytes americanus*) measured as the log of the total biomass consumed in an area (ecosystem) of the northwest Atlantic Ocean (Overholtz et al. 1991, Murawski and Overholtz pers. comm.). Each bar represents the fraction of the respective group of consuming species found in the category corresponding to the labeled rate of resource consumption.

variation for species with such human characteristics. On these grounds, fish, for example, might not serve as examples that are as good as small cetaceans with a body size and metabolic rate similar to that of humans.

Consistency

The examples above show that part of the first criterion of Table 1 can be met by using other species as empirical examples of sustainability to guide management. This approach to management applies at various levels of biological organization, but there is another part to this criterion. Management must apply to the variety of biological systems without conflict; there must be internal consistency. We can not give managers advice at the single species level followed by opposing advice at the ecosystem level.

One form of internal consistency is so obvious as to be nearly trivial. Empirical examples of sustainability are found in systems that are internally consistent. For example, two species cannot consume the same biomass in the examples used above.

But there is a form of consistency that scientists and managers must bring to the process. We must produce and use frequency distributions for both individual resource species and ecosystems. In the example chosen for this paper, the total of biomass harvested from a variety of fish species can not exceed the total established for the marine ecosystem in which they occur. It is important to use frequency distributions such as those in Figures 1 and 2 simultaneously. In other words, it is important to manage at both the single-species and ecosystem levels at the same time.

To fully account for complexity, however, other species frequency distributions must be taken into account (Fowler, in prep.). The number of species consumed was introduced in combining the examples above. There are frequency distributions for counts of the numbers of species consumed by consumers, although it is beyond the scope of this paper to consider this issue in detail. Nevertheless, such distributions would also be considered as information for use in management as being developed here. The number of species consumed would be restricted to within the normal range of natural variation for such counts.

The Management of Fishing Effort

The management of fisheries depends on having a basis for controlling either fishing effort or total takes (Criterion 7, Table 1). Maximum takes established in the use of data such as shown in Figure 1 is straightforward, even though it predictably will be unpopular.

One difficulty will emerge in attempts to avoid the central tendencies of distributions as shown in Figure 1. It might be argued, for example, that a fishing effort resulting in a harvest just below the upper 95% confidence limits of the relevant frequency distributions would be sufficient. This would help avoid the economic impact of changes necessary to achieve harvest reduced even further to correspond to the central tendencies of frequency distributions. However, it must be kept in mind that this is equivalent to arguing for a harvest level that we are 90% sure is larger than optimal, based on the empirical examples of sustainability.

This introduces the issue of burden of proof. In a strict reversal of the burden of proof (Mangel et al., 1996, Dayton, 1998), we would be required to prove that sustainability is maximized for harvest levels other than those corresponding to the central tendencies of frequency distributions such as those of Figure 1 (after being assured that they are applicable to species like humans and corrected for existing human influence, temporal dynamics, using species otherwise similar to humans, etc.).

Dealing with relative harvest rates leads to similar considerations in the application of information at the single-species level (Fig. 2). When we are dealing with relative or specific harvest rates, the conversion of information such as shown in Figure 2 can be converted to fishing effort if we have an established relationship between F (mortality rate caused by fishing) and measures of effort (e.g., boat-days fished). Effort allowed in management would then be based on fishing mortality (or biomass harvest) rates (F) derived from the ESYRs calculated as outlined above. The procedural (e.g., statistical) aspects of these conversions would be subject to the same kinds of scrutiny and scientific study as provided in today's management operations. The difference would be that the choice of F values would not be based on models that we recognize as falling short of representing the reality of the systems in which the empirical examples of sustainability occur.

Meeting other Criteria for Management

We can now see that management based on using other species as empirical examples of sustainability clearly meets a number of the criteria presented in Table 1. When addressing biomass consumption, it applies to individual species (including age groups within a species) and ecosystems (Criterion 1). At the core of this approach is maintaining elements of ecosystems within their normal range of natural variation (Criterion 3) by considering biomass consumption an option for humans (i.e., commercial fishing) within ecosystems (Criterion 8) and exercising constraint (control) where it is an option (Criterion 7). Maintaining ecosystems within their normal range of natural variation is beyond direct human control. It may be promoted or facilitated, however, through human action to control human influence. Guidance for this control is found in the normal ranges of natural variation of distributions like Figures 1 and 2. Controlling human influence will allow the other species and ecosystems to exhibit homeostatic dynamics. Precaution can be exercised in avoiding the risks and constraints that prevent the accumulation of species in the tails of species frequency distributions while simultaneously achieving sustainability (Criterion 4). This approach uses the information (Criterion 5) derived from species frequency distributions.

We are left with several elements of Table 1, however, that have not been mentioned. These are considered in the remainder of this section, again restricting the treatment to the example of managing the rates of biomass harvests (consumption) by humans.

It is easy to see how the approach would be applied to "management at the biosphere level," a form of management that would be the next issue of importance after developing an approach that works at the ecosystem level. To do so, the total biomass consumption for other species (with similar body size, metabolic rate, trophic level and other characteristics similar to those of humans) would be estimated based on their total population size. The resulting species frequency distribution would be used in parallel with the process laid out above for ecosystems and single species. We would then have to deal with the total for consumption of biomass by humans from the various ecosystems from which harvests are extracted. This total would be constrained to the central tendency for the totals for other species. This clearly leads to serious implications for our species as laid out in Fowler (in prep.), and is well beyond the scope of this paper.

How does the approach account for reality and its complexity (Criterion 2, Table 1) to involve interdisciplinary considerations (Criterion 5)? The species found in the various frequency distributions are exposed to, and emerge from, the complexity of factors that result in the distributions. This reality includes the entire set of ecological mechanics involved in such things as predator/prey interactions, competition, and geographic distribution. The genetic information (Criterion 5) in its contribution to what species are, and where they fall in species frequency distributions, is taken into account as are all of the evolutionary dynamics that resulted in their evolution. Both the evolutionary dynamics experienced by species and the evolutionary field supplied by their environment (the set of selective forces to which they are exposed, including those from interspecific interactions) are accounted for as part of the elements contributing to the formation of frequency distributions among species. Species frequency distributions are analogous to the probability distributions that emerge from Bayesian statistical analysis (Fowler et al., in prep.), except that the Monte Carlo-like models are real physical models (instead of computer models) and the code is genetic (rather than computer code).

Thus, the challenge of having an interdisciplinary contribution to decision-making is partially solved. The complexity of reality, each piece of which the respective science takes as a focus for study, is already accounted for. The impossibility of knowing the relative importance of the results of any particular field of science is no longer a problem. However, we can not overemphasize the importance of the contributions of each field of science in producing the information for species frequency distributions and their correlative interrelationships. Here, interdisciplinary contributions are invaluable (Criteria 5 and 6, Table 1). The same holds for the importance of monitoring the systems that we influence with our harvest strategies (species, ecosystems, etc. from which we consume biomass) to observe whether or not they achieve their own states within the respective normal ranges of natural variation (Criterion 6).

Nature's Monte Carlo Experiments in Sustainability

In part (and only in part) frequency distributions such as those shown here are the results of trial-and-error processes of natural selection. Part of natural selection is that of selective extinction and speciation (Lewontin 1970, Slatkin 1981, Arnold and Fristrup 1982, Fowler and MacMahon 1982, Levinton 1988, Eldredge 1989, Williams 1992, Fowler in prep). Species emerge as examples of sustainability through the trial-and-error process of natural selection in being exposed to the variety of factors that we wish to take into account (Criterion 2, Table 1). Species frequency distributions emerge because the species in them are exposed to reality including the ecological mechanics of interactions among species (e.g., predator-prey relationships, and competition) that we recognize as important elements of ecosystems. By using the guidance of empirical examples of sustainability, we would account for ecosystems themselves.

Thus, as mentioned above, species, which are made up of individuals, are like physical Monte Carlo trial-and-error models to result in a form of Bayesian integration in the frequency distributions. They are tested in the face of the suite of risks and complexities of their environment. The effects of these factors are integrated into the information content of species frequency distributions. Even extinction and related risks are taken into account. Existing species, serving as empirical examples of sustainability (rates of foraging that are sustainable in the examples used in this paper), and represented in frequency distributions, have not succumbed to the risks leading to extinction as a process that has removed billions of species as failures in the grand Monte Carlo experiment. Collective risks prevent the accumulation of species in the tails of species frequency distributions and especially beyond the normal ranges of natural variation.

Conclusions

It has been argued above that non-human species serve as examples of sustainability, using rates of foraging from ecosystems and individual resource species as examples. We humans are not in a position to claim that we are our own example (e.g., by using cases where fishing has been carried out for decades at rates beyond the limits of species frequency distributions such as shown in Figs. 1 and 2). Even the species in the tails of these distributions cannot be viewed as particularly good examples. Decades of fishing cannot weigh against hundreds of thousands of years of evolutionary history. Part of the variance in the frequency distributions observed today stems from short-term ecological mechanical variation (and observational variance). Such information would be better if averaged (integrated) over longer periods of time. Emerging patterns among systems compared across varying environmental factors (latitude, mean temperature, etc.) will be of similar value. Science is faced with an immense challenge in providing such information.

A further challenge is that of research to elucidate the correlative information relating biomass consumption to trophic level, body size, metabolic rate and other species-level features. Such patterns will be very important in refining the nature of the frequency distributions and their information content as the source of guidance for management as developed in this paper.

The information in hand is preliminary. An interdisciplinary effort is required to proceed.

However, there is basis for proceeding. The form of management outlined above meets all of the 8 criteria laid out in Table 1. The management of biomass consumption (specifically the harvest of fish) is only one example of the application of the approach (Fowler in prep.).

Finally, the acceptance and implementation of this approach may be even more of a challenge than the scientific endeavor needed to produce more reliable information. Considerable institutional, social, economic, political, and behavioral changes are involved. The degree to which they are a challenge, however, is more a measure of the size of problems that we have to solve than justification for avoiding the work required.

Acknowledgements

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